

ENERGY RELEASE DUE TO ANTINEUTRINO UNTRAPPING FROM HOT QUARK STARS *

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An equation of state for 2-flavor quark matter (QM) with diquark condensation under the conditions for compact stars - β -equilibrium, charge and color neutrality- is presented. Trapped antineutrinos prevent the formation of the diquark condensate at moderate densities above a critical value of the antineutrino chemical potential $\mu_{\bar{\nu}_e}^c$. The following consequences are presented: 1) The star develops a 2-phase structure ($\mu_{\bar{\nu}_e} \geq \mu_{\bar{\nu}_e}^c$): a color superconducting QM core and a normal QM shell. 2) During the cooling, when the temperature is small enough ($T < 1$ MeV) the antineutrino mean free path becomes larger than the thickness of the normal QM shell and the antineutrinos get untrapped in a sudden burst. The energy release is estimated as $\simeq 10^{52}$ erg and an antineutrino pulse is expected to be observed.

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1. Introduction

It has been proposed that cold dense quark matter should be in a superconducting state with the formation of a diquark condensate^{1,2}. The consequences of the diquark condensation for the configuration and the cooling behaviour of compact stars have been broadly studied^{3,4,5,6} and the question if this phase can be detected by the signatures still remains⁷.

Also the engine for the most energetic phenomena in the universe like supernova explosions and gamma ray burst does not have a satisfactory explanation yet⁸ and it has been proposed that the energy involved could be related with the occurrence of the color superconductivity phase^{9,10}.

Since the pairing energy gap in quark matter is of the order of the Fermi energy, the diquark condensation gives a considerable contribution to the equation of state (EoS) that is estimated of the order of $(\Delta/\mu)^2$. Disregarding relativistic effects, the total binding energy release in the core of a cooling protoneutron star has been estimated as $(\Delta/\mu)^2 M_{\text{core}} \simeq 10^{52}$ erg. But, if relativistic effects are considered, the gravitational mass defect of the cooling star decreases when diquark condensation is included and there is no explosive process⁶ possible since the color superconductivity transition is second order.

In this work a new mechanism of releasing the energy in an explosive way is presented (for the original idea see¹¹). During the collapse of a protoneutron star antineutrinos are produced by the β -processes and remain trapped due to the small mean free path. This increases the asymmetry in the system and therefore the diquark condensation is inhibited at moderate densities. So, a two-phase structure develops in the star: a superconducting interior and a surrounding shell of normal quark matter, the latter being opaque to antineutrinos for $T \geq 1$ MeV¹². In the cooling process the antineutrino mean free path increases above the size of this normal matter shell and an outburst of neutrinos occurs releasing an energy of about $10^{51} - 10^{52}$ erg. This first order phase transition leads to an explosive phenomenon in which a pulse of antineutrinos could be observed.

1.1. Equation of state for 2-flavour quark matter

A nonlocal chiral quark model for 2-flavour $\{u, d\}$ and three color $\{r, b, g\}$ superconducting (2SC) quark matter in the mean field approximation is used, for details see^{6,13}. The order parameters are the mass gap ϕ_f and the diquark gap Δ for the chiral and superconducting phase transitions respectively. As in¹³, the following chemical potentials are introduced:

$\mu_q = (\mu_u + \mu_d)/2$ for quark number, $\mu_I = (\mu_u - \mu_d)/2$ for isospin asymmetry and μ_8 for color charge asymmetry. The deviation in the color space is considered $\mu_8 \ll \mu_q$, so the effect of considering μ_8 is neglected.

The quark thermodynamic potential is expressed as ¹⁴

$$\begin{aligned} \Omega_q(\phi, \Delta; \mu_q, \mu_I, T) + \Omega_{vac} = & \frac{\phi^2}{4G_1} + \frac{\Delta^2}{4G_2} \\ & - \frac{2}{2\pi^2} \int_0^\infty dq q^2 (N_c - 2) \{ 2E_\phi + \omega [E_\phi - \mu_q - \mu_I, T] \\ & + \omega [E_\phi - \mu_q + \mu_I, T] + \omega [E_\phi + \mu_q - \mu_I, T] + \omega [E_\phi + \mu_q + \mu_I, T] \} \\ & - \frac{4}{2\pi^2} \int_0^\infty dq q^2 \{ E_+ + E_- + \omega [E_\phi^- - \mu_I, T] \\ & + \omega [E_\phi^- + \mu_I, T] + \omega [E_\phi^+ - \mu_I, T] + \omega [E_\phi^+ + \mu_I, T] \} \end{aligned} \quad (1)$$

with

$$\omega[E, T] = T \ln [1 + \exp(-E/T)] . \quad (2)$$

The dispersion relations for the quarks of unpaired and paired colors are respectively,

$$E_\phi^2 = q^2 + (m + F^2(q)\phi)^2 \quad (3)$$

$$E_\phi^{\pm 2} = (E_\phi \pm \mu)^2 + F^4(\bar{q})\Delta^2 \quad (4)$$

The interaction between the quarks is implemented via a Gaussian form-factor function $F(q)$ in the momentum space (Gaussian types give stable hybrid configurations ⁷) as $F(q) = \exp(-q^2/\Lambda^2)$.

The parameters $\Lambda = 1.025$ GeV, $G_1 = 3.761 \Lambda^2$ and $m_u = m_d = m = 2.41$ MeV are fixed by the pion mass, pion decay constant and the constituent quark mass at $T = \mu = 0$ ¹⁵. The constant G_2 is a free parameter of the approach and is fixed as $G_2 = 0.86 G_1$.

1.1.1. *Stellar matter conditions*

The stellar matter in the quark core of compact stars is considered to consists of u and d quarks and leptons (electrons e^- and antineutrinos $\bar{\nu}_e$) under the following conditions

- β -equilibrium $d \longleftrightarrow u + e^- + \bar{\nu}_e, \quad \mu_e + \mu_{\bar{\nu}_e} = -2\mu_I,$
- Charge neutrality $\frac{2}{3}n_u - \frac{1}{3}n_d - n_e = 0, \quad n_B + n_I - 2n_e = 0,$
- Color neutrality $n_8 = 0, \quad 2n_{qr} - n_{qb} = 0,$

where $n_j = \frac{\partial \Omega}{\partial \mu_j} \Big|_{T, \phi=\phi_0, \Delta=\Delta_0}$ are the number densities corresponding to the chemical potential μ_j defined above.

The lepton contributions ($l = e, \bar{\nu}_e$) as ideal Fermi gases

$$\Omega_l(\mu, T) = -\frac{1}{12\pi^2}\mu^4 - \frac{1}{6}\mu^2 T^2 - \frac{7}{180}\pi^2 T^4 \quad (5)$$

are added to the quark thermodynamical potential

$$\Omega(\phi, \Delta; \mu_q, \mu_I, \mu_e, T) = \Omega_q(\phi, \Delta; \mu_q, \mu_I, T) + \Omega_e(\mu_e, T) + \Omega_{\bar{\nu}_e}(\mu_{\bar{\nu}_e}, T). \quad (6)$$

The baryon chemical potential $\mu_B = 3\mu_q - \mu_I$ is introduced as the conjugate of the baryon number density n_B .

The Ω function can have several minima in the ϕ, Δ plane, an example is shown in Fig. 1. The global minimum represents the stable equilibrium of the system and the minima search is performed solving the gap equations

$$\frac{\partial \Omega}{\partial \phi} \Big|_{\phi=\phi_0; \Delta=\Delta_0} = \frac{\partial \Omega}{\partial \Delta} \Big|_{\phi=\phi_0; \Delta=\Delta_0} = 0 \quad (7)$$

under the conditions that are mentioned above for the stellar interior.

The thermodynamics of the system, e.g. pressure P , energy density ϵ , number density n and entropy density s , is defined via this global minimum

$$\Omega(\phi_0, \Delta_0; \mu_B, \mu_I, T) = \epsilon - Ts - \mu_B n_B - \mu_I n_I = -P. \quad (8)$$

To fulfill the charge neutrality condition (see Fig. 2, right) a mixed phase between a subphase with diquark condensation (subscript $\Delta > 0$) and normal quark matter subphase (subscript $\Delta = 0$) is defined via the Glendenning construction. The Gibbs condition for equilibrium at fixed T and μ_B is that the pressure of the subphases should be the same

$$P = P^{\Delta>0}(\mu_B, \mu_I, \mu_e, T) = P^{\Delta=0}(\mu_B, \mu_I, \mu_e, T). \quad (9)$$

The volume fraction χ that is occupied by the subphase with diquark condensation is defined by the charge Q in the subphases,

$$\chi = Q_{\Delta>0} / (Q_{\Delta>0} - Q_{\Delta=0}), \quad (10)$$

and is plotted on the right panel in Fig. 2 for different antineutrino chemical potentials as a function of μ_B . In the same way, the number

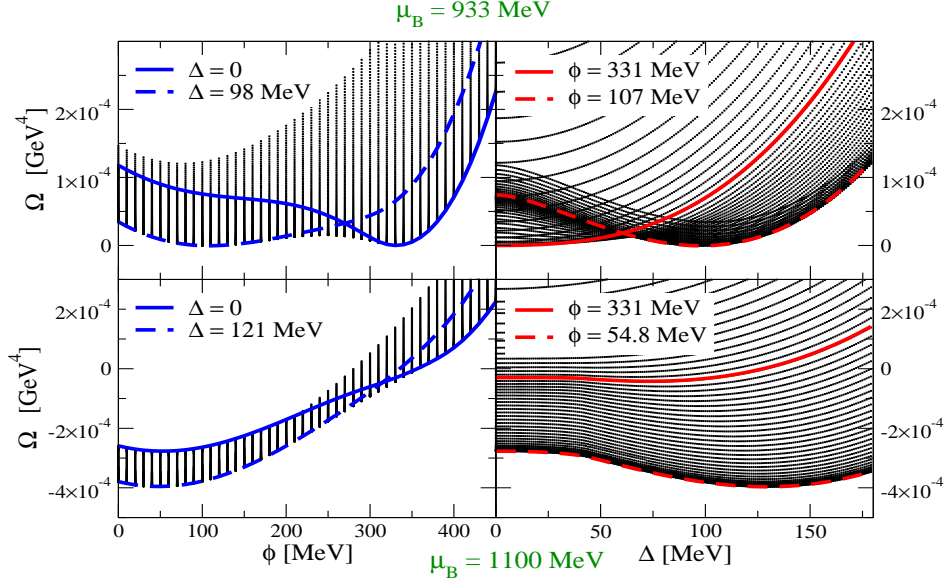


Figure 1. Cuts of the thermodynamic potential $\Omega(\phi, \Delta; \mu_B, \mu_I, T = 0)$ in the planes $\Delta = \text{const}$ (on the left) and $\phi = \text{const}$ (on the right) for two different constant values of μ_B and the corresponding μ_I . For $\mu_B = 933$ MeV (upper panel) two degenerate minima can coexist at the values: $\phi = 331$ MeV, $\Delta = 0$ (solid lines) and $\phi = 107$ MeV, $\Delta = 98$ MeV (dashed lines). For $\mu_B = 1100$ MeV (lower panel) the minimum with a nonvanishing diquark $\Delta = 121$ MeV and $\phi = 54.8$ MeV (dashed lines) is preferable. This corresponds to a first order transition from the vacuum to a superconducting phase. In this example $G_2/G_1 = 1$ was taken.

densities for the different particle species j and the energy density are given by

$$n_j = \chi n_{j\Delta>0} + (1 - \chi) n_{j\Delta=0} , \quad (11)$$

$$\epsilon = \chi \epsilon_{\Delta>0} + (1 - \chi) \epsilon_{\Delta=0} . \quad (12)$$

1.1.2. Equation of state with trapped antineutrinos

Increasing the antineutrino chemical potential $\mu_{\bar{\nu}_e}$ increases the asymmetry in the system and this shifts the onset of the superconducting phase transition to higher densities.

Above a critical value of $\mu_{\bar{\nu}_e} \geq \mu_{\bar{\nu}_e}^c \simeq 30$ MeV (see critical value in Fig.

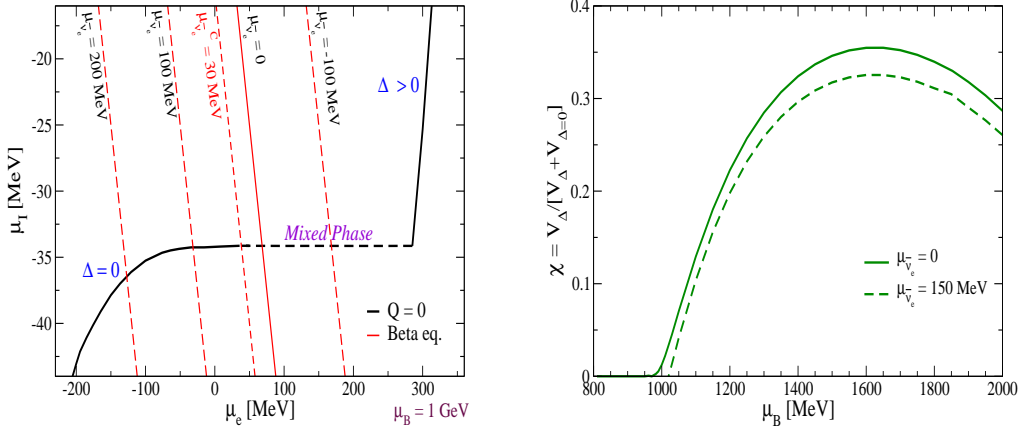


Figure 2. **Left:** Solutions of the gap equations and the charge neutrality condition (solid black line) in the μ_I vs. μ_e plane. Two branches are shown: states with diquark condensation on the upper right ($\Delta > 0$) and states from normal quark matter ($\Delta = 0$) on the lower left. The plateau in between corresponds to a mixed phase. The lines for the β -equilibrium condition are also shown (solid and dashed red lines) for different values of the (anti)-neutrino chemical potential. The stellar matter should satisfy both conditions (intersection of the corresponding lines) and therefore for $\mu_{\bar{\nu}_e} = 0$ a mixed phase is preferable. **Right:** Volume fraction χ of the phase with nonvanishing diquark condensate obtained by a Glendenning construction of a charge-neutral mixed phase. Results are shown for two different values of $\mu_{\bar{\nu}_e}$.

2, on the left) first a normal quark matter phase occurs and then the phase transition to superconducting matter takes place, see Fig. 3, on the left.

The consequences for the equation of state can be seen on the right of the Fig. 3: the onset of the superconductivity in quark matter is shifted to higher densities and the equation of state becomes harder.

1.2. Quark stars and antineutrino trapping

The configurations for the quark stars are obtained by solving the Tolman-Oppenheimer-Volkoff equations for a set of central quark number densities n_q for which the stars are stable.

In Fig. 4 the configurations for different antineutrino chemical potentials are shown. The equations of state with trapped antineutrinos are softer and therefore this allows more compact configurations. The presence of antineutrinos tends to increase the mass of the star for a given central

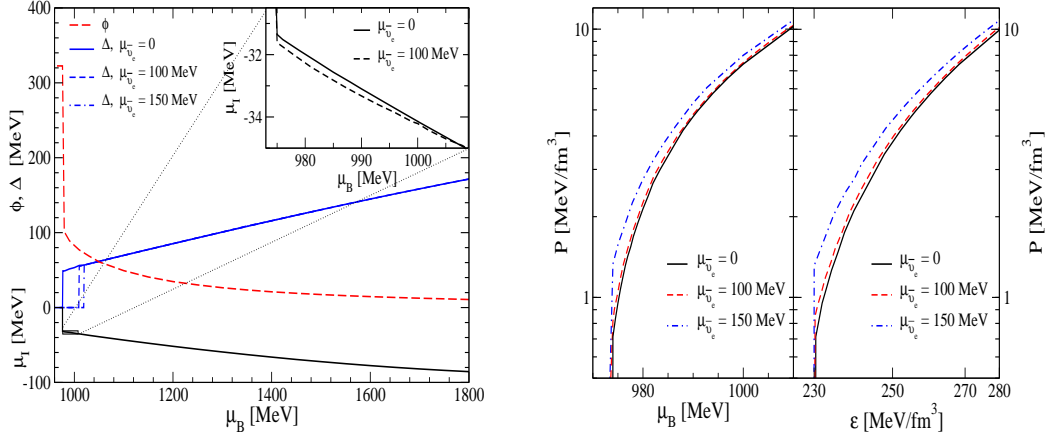


Figure 3. **Left:** Solutions of the gap equations and μ_I as a function of μ_B . Increasing the antineutrino chemical potential increases the asymmetry in the system and the superconducting phase is inhibited at moderate densities. **Right:** Equation of state for different values of $\mu_{\bar{\nu}_e}$ of trapped antineutrinos. As $\mu_{\bar{\nu}_e}$ increases the equation of state becomes harder.

density.

A reference configuration with total baryon number $N_B = 1.51 N_\odot$ (where N_\odot is the total baryon number of the sun) is chosen and the case with (configurations *A* and *B* in Fig. 4) and without antineutrinos (*f* in Fig. 4) are compared. A mass defect can be calculated between the configurations with and without trapped antineutrinos at constant total baryon number and the result is shown on the right panel of Fig. 4). The mass defect could be interpreted as an energy release if the configurations *A, B* with antineutrinos are initial states and the configuration *f* without them is the final state of a protoneutron star evolution.

1.2.1. Protoneutron star evolution with antineutrino trapping

After the collapse of a protoneutron star the star cools down by surface emission of photons and antineutrinos. Antineutrinos are trapped because they were generated by the direct β -process in the hot and dense matter and could not escape due to their small mean free path. The region of the star where the temperature falls below the density dependent critical value for diquark condensation, will transform to the color superconducting state

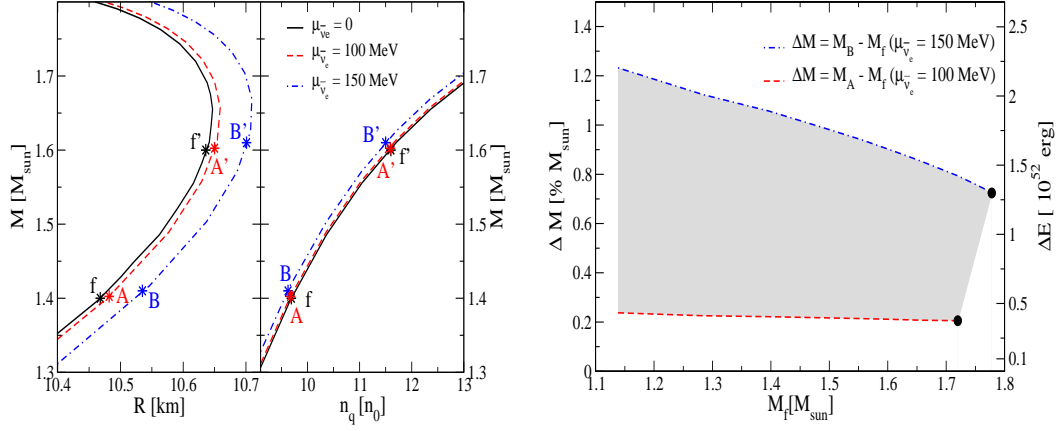


Figure 4. **Left:** Quark star configurations for different antineutrino chemical potentials $\mu_{\bar{\nu}_e} = 0, 100, 150$ MeV. The total mass M in solar masses ($M_{\text{sun}} \equiv M_{\odot}$ in the text) is shown as a function of the radius R (left panel) and of the central number density n_q in units of the nuclear saturation density n_0 (right panel). Asterisks denote two different sets of configurations (A,B,f) and (A',B',f') with a fixed total baryon number of the set. **Right:** Mass defect ΔM and corresponding energy release ΔE due to antineutrino untrapping as a function of the mass of the final state M_f . The shaded region is defined by the estimates for the upper and lower limits of the antineutrino chemical potential in the initial state $\mu_{\bar{\nu}_e} = 150$ MeV (dashed-dotted line) and $\mu_{\bar{\nu}_e} = 100$ MeV (dashed line), respectively.

which is almost transparent to (anti)neutrinos. But nevertheless due to the trapped antineutrinos there is a dilute normal quark matter shell which prevents neutrino escape from the superconducting bulk of the star, see Fig. 5 and Fig. 6. The criterion for the neutrino untrapping transition is to cool the star below a temperature of about 1 MeV when the mean free path of neutrinos becomes larger than the shell radius¹⁶. If at this temperature the antineutrino chemical potential is still large then the neutrinos can escape in a sudden outburst. If it is small then there will be only a gradual increase in the luminosity. An estimate for the possible release of energy within the outburst scenario can be given via the mass defect defined in the previous subsection between an initial configuration with trapped neutrinos (state A or B) and a final configuration without neutrinos (state f).

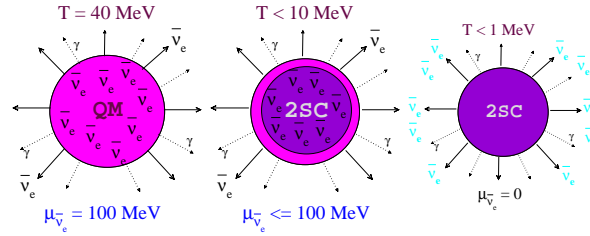


Figure 5. Left graph: Quark star cooling by antineutrino and photon emission from the surface. Middle graph: Two-phase structure develops due to the trapped antineutrinos: a normal quark matter shell and a superconducting interior. Right graph: Antineutrino untrapping and burst-type release of energy.

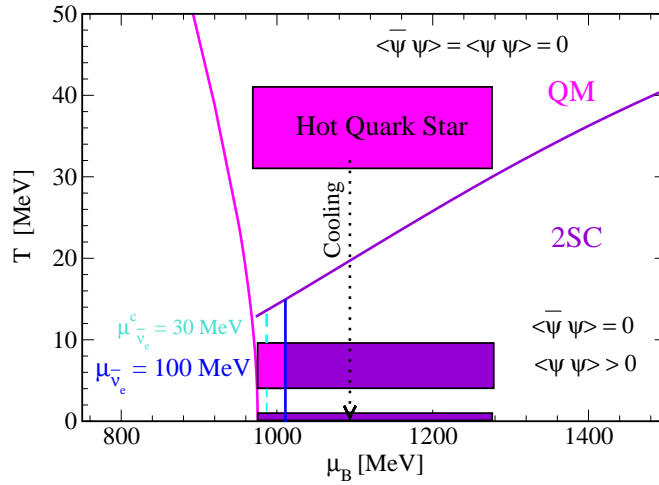


Figure 6. Star evolution corresponding to Fig. 5 plotted in the phase diagram

2. Conclusions

The effects of trapped antineutrinos on the diquark condensates in quark star configurations are investigated. At fixed baryon number the energy release in the antineutrino untrapping transition is of the order of 10^{52} erg. This is a first order transition and leads to an explosive release of energy that could help to explain energetic phenomena in the universe like gamma ray bursts or supernova explosions.

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